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FLOW STABILITY BEYOND UNIT ROUGHNESS,(U)

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FOREIGN TECHNOLOGY DIVISION

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FLOW STABILITY BEYOND UNIT ROUGHNESS

by

S. Ya. Gertsenshteyn

FOREIGN TECHNOLOGY DIVISION

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EDITED TRANSLATION

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By: S. Ya. Gertsenshteyn

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К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α	α	α	Nu	Ν	ν	
Beta	Β	β		Xi	Ξ	ξ	
Gamma	Γ	γ		Omicron	Ο	ο	
Delta	Δ	δ		Pi	Π	π	
Epsilon	Ε	ε	ϵ	Rho	Ρ	ρ	ϱ
Zeta	Ζ	ζ		Sigma	Σ	σ	ς
Eta	Η	η		Tau	Τ	τ	
Theta	Θ	θ	ϑ	Upsilon	Υ	υ	
Iota	Ι	ι		Phi	Φ	φ	ϕ
Kappa	Κ	ϰ κ	κ	Chi	Χ	χ	
Lambda	Λ	λ		Psi	Ψ	ψ	
Mu	Μ	μ		Omega	Ω	ω	

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

---

rot	curl
lg	log

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Flow Stability Beyond Unit Roughness

S.Ya. Gertsenshteyn

Roughness of a body's surface is one of the main factors influencing the position of the point of transition between a laminar boundary layer and a turbulent one.

This paper explains the influence of two-dimensional unit roughness on the origin of turbulence. More accurately, a study is made here of flow stability beyond two-dimensional unit roughness. Many experimental studies have been devoted to studying the influence of two-dimensional unit roughness on the origin of turbulence [1]. This is explained by the value this problem has for practical application. As a very simple example can be given the problem of selecting the depth and shape of a welding seam, questions relating to aircraft, etc.

If, as is usually the case, the flow far from the surface is considered close to plane-parallel, then the problem of flow stability as far as infinitely small disturbances are concerned boils down to the problem of finding eigenvalues of the Orr-Sommerfeld equation with homogeneous boundary conditions:

$$\frac{i}{\alpha\tilde{R}}\left(\varphi^{IV} - 2\alpha^2\varphi'' + \alpha^4\varphi\right) + (U - c)(\varphi'' - \alpha^2\varphi) - U''\varphi = 0, \quad (1)$$

$$\varphi(0) = 0, \quad \varphi(\infty) = 0, \quad \varphi'(0) = 0, \quad \varphi'(\infty) = 0. \quad (2)$$

Here, $U(y)$ is the velocity beyond unit roughness, $\tilde{R} = u_0 \overset{\alpha}{\cancel{d}}/\nu$ is the local Reynolds number (d is the depth of roughness; u_0 is the velocity at a roughness level remote from the surface, and

ν is the coefficient of viscosity). All remaining symbols here are defined by the fact that flow function for a disturbance of ψ is written in the form:

$$\psi = \varphi(y) \exp\{i\alpha(x - ct)\}, \alpha = \alpha_r + i\alpha_i$$

Entering the discussion below will be one more Reynolds number:

$$R_1 = \frac{U_\infty \delta_1}{\nu} \quad (\delta_1 = 5{,}0\sqrt{x\nu/U_\infty})$$

and a frequency of

$$\gamma = \alpha_r c$$

A solution to the problem was sought for eigenvalues according to [2]. Calculations were made for different positions of the unit surface with respect to the front edge of a plate with a fixed external streamline flow velocity (i.e., with different Reynolds numbers for the main stream, $R_1 = U_\infty \delta/\nu$). The velocity profile, $U^*(y)$, beyond the unit surface was taken in the following form:

$$U^*(y) = \begin{cases} U(y) + \left[\upsilon\left(y\left(\frac{d}{\delta_1}\right)^{-1}\right) - y\left(\frac{d}{\delta_1}\right)^{-1} \dot{U}\left(\frac{d}{\delta_1}\right) \right] & \text{when } 0 \leq y < \frac{1}{3} \\ U(y) & \text{when } \frac{1}{3} \quad y < \infty \end{cases}$$

Here $U(y)$ is the Blasius profile, $\upsilon(y)$ is the velocity profile beyond the unit surface computed in [3] with a corresponding Reynolds number value of $\tilde{R}$.

Neutral curves and steady growth curves were plotted, giving the relationship between the local Reynolds number, $\tilde{R} = u_0 d/\nu$, the wavelength of the perturbation, $\lambda = 2\pi/\alpha r$, the frequency of perturbation, $\gamma = \alpha_r c$, and the gain, α_i . Typically, the first manifestations of instability (with small values of the local Reynolds number, $\tilde{R}$) are observed in experiments sufficiently far beyond the unit surface, i.e., exactly where the flow is close to plane-parallel. Here the velocity profile, $U(y)$, in specific computations corresponds to a

velocity distribution in the stream at a distance of five gauge numbers downstream from the unit surface (the depth of the unit surface, d , is understood to be typical).

As a result of calculations of flow instability beyond the unit surface it was found that the unit surface can show a stabilizing effect with a sufficiently low local Reynolds number. Apparently, the appearance of a point of inflection in the velocity profile near the wall has an insubstantial influence on stability owing to the stabilizing effect of the wall, and the increase in fullness of the velocity profile proves to be more important. Furthermore, the fullness of the velocity profile increases at a very dangerous point--in the vicinity of the critical layer. Critical Reynolds numbers for the main stream with similar comparatively moderate distortions of the initial profile increase markedly. For example, when $\tilde{R} = u_0 d/\nu = 3$ and $d = (1/2s)\delta$, the maximal relative deviation from the initial profile, $\max_y [U^*(y) - U(y)]/U(1)$, is less than one percent in absolute value, and the critical Reynolds number for this slightly altered profile increases by almost a factor of 1.5 (Fig. 2 and 3).

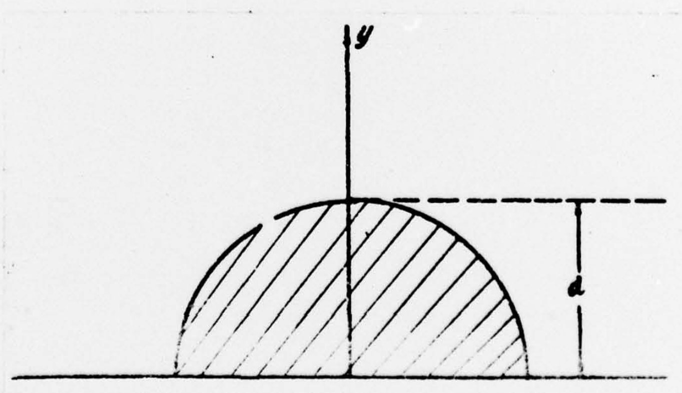


Fig. 1

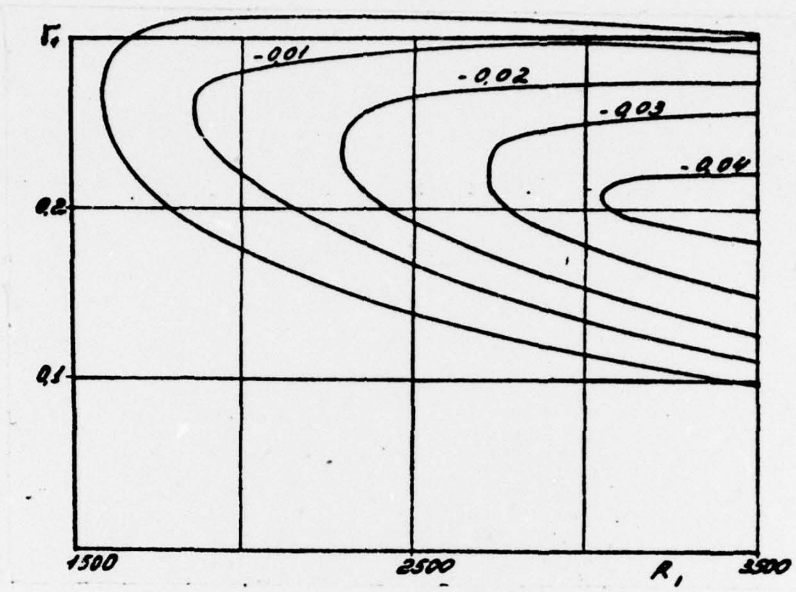

Γ_1
-0.01
-0.02
-0.03
-0.04
0.2
0.1
1500
2500
R_1
3500

Fig. 2.

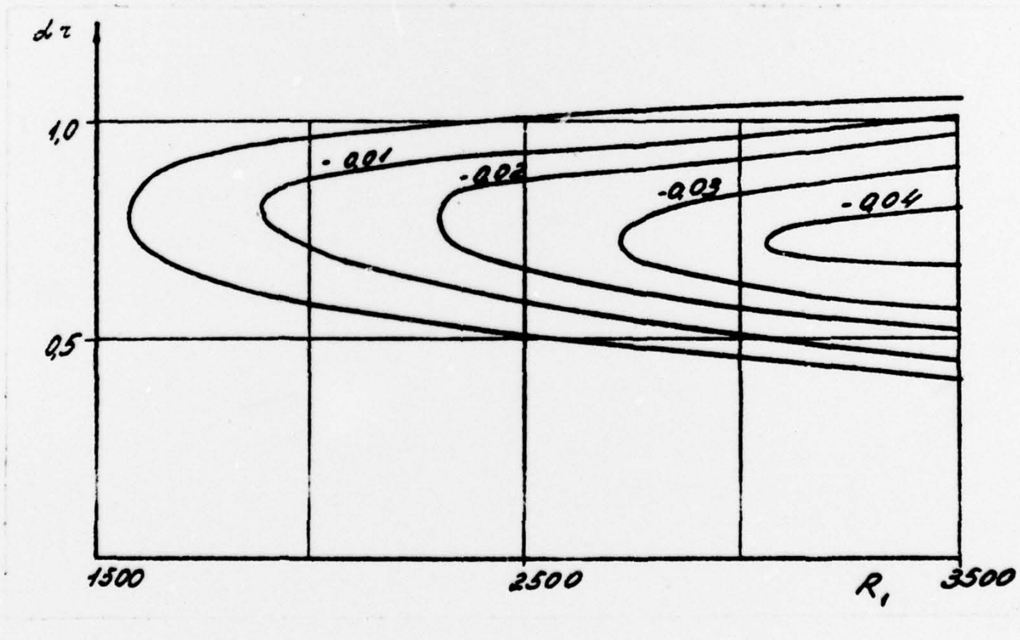
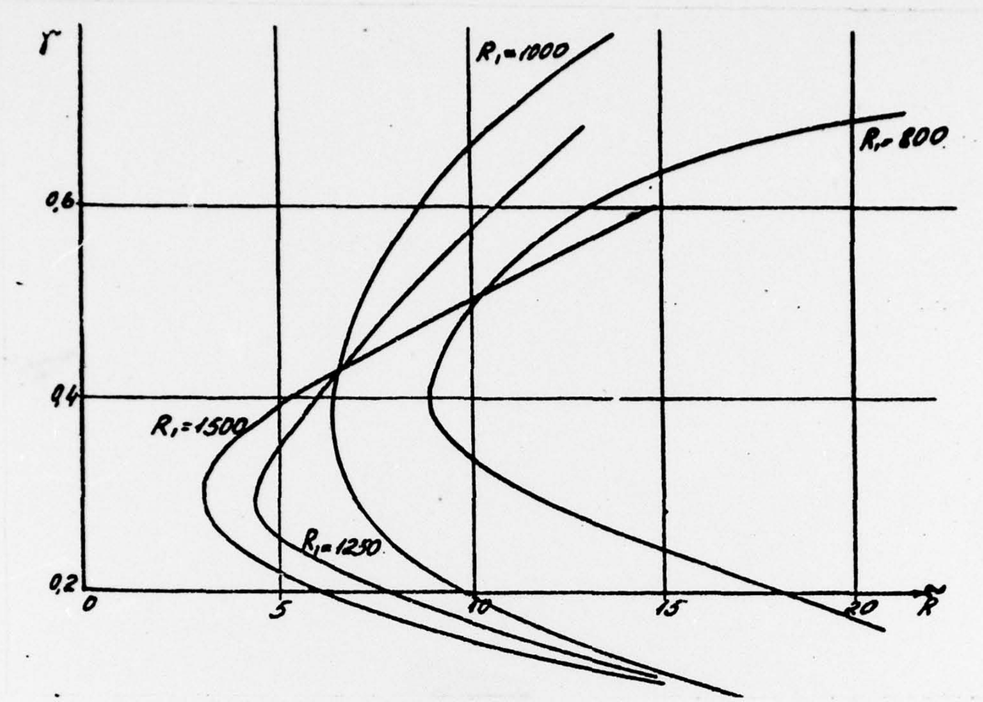
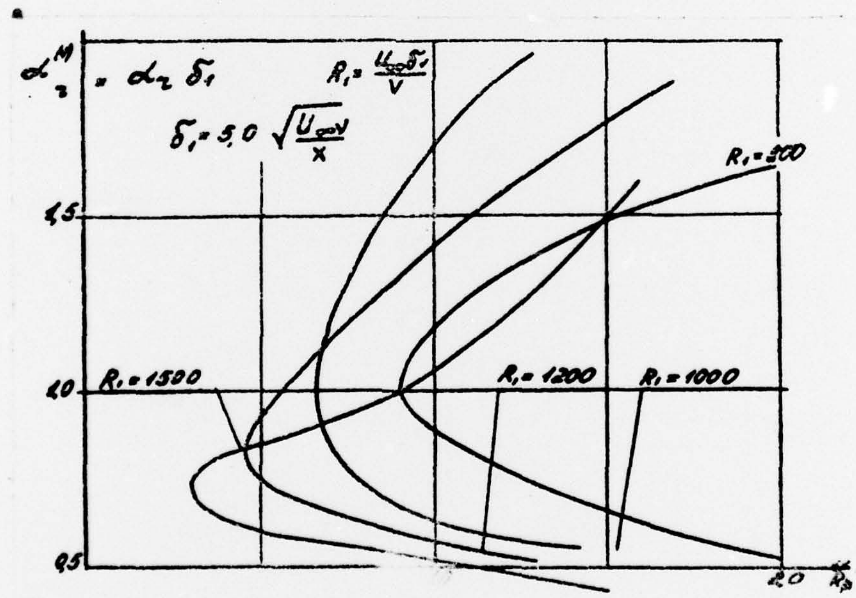

αr
1,0
0,5
-0.01
-0.02
-0.03
-0.04
1500
2500
R_1
3500

Fig. 3



γ
R₁=1000
R₁=800
0,6
0,4
R₁=1500
R₁=1250
0,2
0
5
10
15
20
R

Fig. 4



R₁=1500
R₁=1200
R₁=1000
R₁=800
1,5
1,0
0,5
2,0

Fig. 5

The range of dangerous wave numbers is somewhat reduced.

Fig. 4 and 5 show the relationships between the local Reynolds number and the wave perturbation characteristics introduced above ($\alpha = \alpha_r + i\alpha_i$; $\gamma = \alpha_r c$) with main stream Reynolds numbers, $R_1 = U_\infty(\delta_1/\nu)$ equal respectively to 800, 1000, 1200, and 1500. In Fig. 5 the relationship between $\tilde{R}$, α, and γ is shown only for $\tilde{R} > 4$. Calculations demonstrate that the most dangerous wave numbers in all cases considered lie approximately between 0.93 and 1.2. The frequencies corresponding to these wave numbers lie in the range of 0.3 to 0.4. The maximal values of wave numbers and frequencies on all neutral curves increase with an increase in the local Reynolds number, $\tilde{R}$. Within the range of variation of $\tilde{R}$ considered, the maximal value of the wave number is $\alpha^* \cong 1.7$, and the maximal frequency value is $\gamma^* \cong 0.72$.

The great relative wavelength of unstable perturbations draws attention. In dimensional variables $\lambda^{(2)}_{min} \cong 3.7$. A similar feature is typical of the neutral curve computed by Tolmin [1] for the boundary layer, $\lambda_{min} \cong 6\delta$, where $\delta = 5.2\sqrt{(\nu x/\upsilon_\infty)}$ is the distance to the forward edge, and υ_∞ is the velocity at infinity. It is easy to see that the wavelengths of dangerous perturbations for the boundary layer are greater than in the case considered. It can also be seen that the phase velocity, $C_r = \gamma/\alpha_r$, on the neutral curve varies slightly. For example, when the Reynolds number, $\tilde{R}$, varies from 9 to 20 (the Reynolds number of the main stream, R_1 , equals 800), the phase velocity varies from 0.4 to 0.42 (for the upper branch of the neutral curve) or from 0.4 to 0.33 (for the lower branch of the neutral curve). Especially striking is the strong dependence of wave numbers, α_r , gain α_i, and frequency, γ , on local Reynolds numbers. When the Reynolds number, $\tilde{R} = u_0 d/\nu$, varies from six to ten ($R_1 = 1000$), the highest of the dangerous frequencies increases approximately twofold

(from 0.32 to 0.65), the frequency of the most dangerous perturbation increases approximately by 1.4 (from 0.31 to 0.43), and the wavelength of the most dangerous perturbation by 1.3 (from 0.91 to 1.18).
The increase in the range of dangerous wave numbers and frequencies corresponds to the manifestation in the problem of one more characteristic dimension (the depth of the unit roughness), which is considerably smaller than the thickness of the boundary layer. The gain $(-\alpha_i)$ even with moderate Reynolds numbers, $\tilde{R} = u_0\tilde{\delta}/\nu$, varies considerably when the unit roughness is added to the stream. In particular, when $R_1 = 1000$, for the Blasius profile $\max(-\alpha_i) \cong -0.05$, and when $\tilde{R} = 10$ and $R = 1000$, $\max(-\alpha_i) \cong 0.064$. We recall that for the Blasius profile $\max(-\alpha_i) \cong 0.03$ even when $R = 2500$. The situation is somewhat more complex when R_1 Reynolds numbers are close to critical. For example, when the Reynolds number is 1200 the flow in the boundary layer is unstable ($\max(-\alpha_i) = 0.002$), and it can become stable when the unit roughness is added. So, when $\tilde{R} = 3$ the flow is steady ($\max(-\alpha_i) = -0.0145$). The corresponding curves are shown in Fig. 6 and Fig. 7.

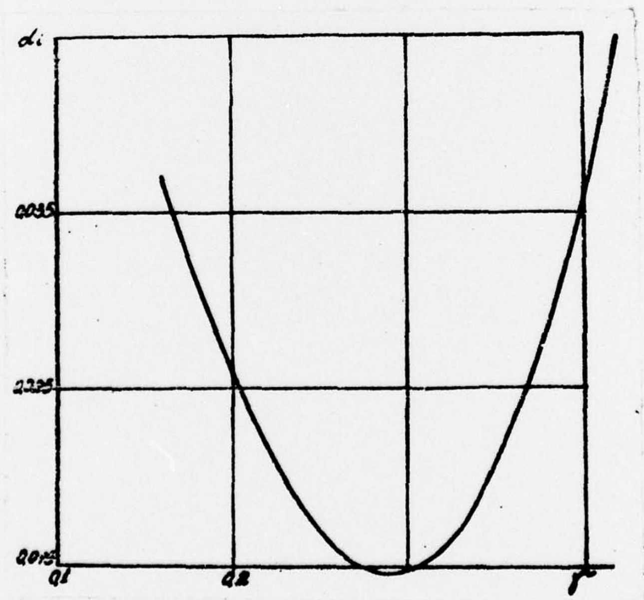


Fig. 6

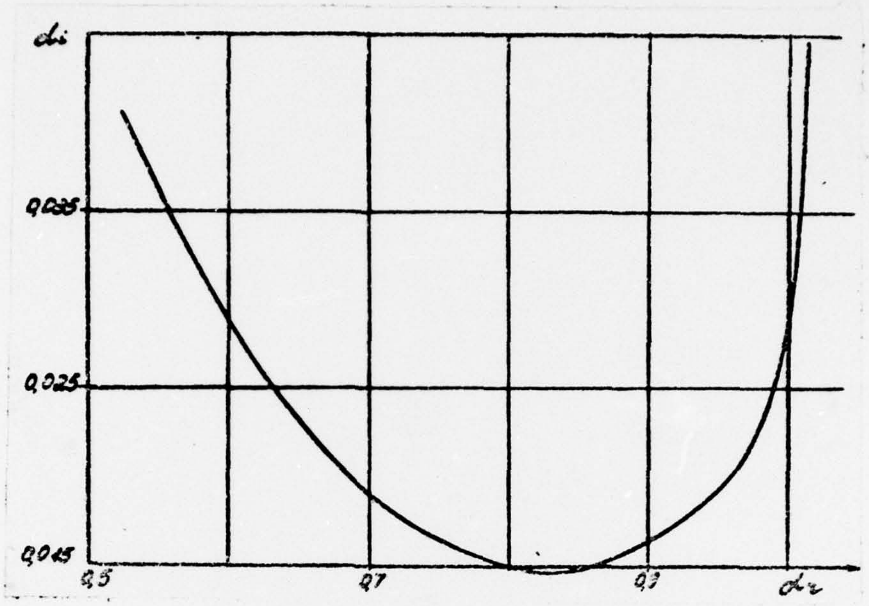


Fig. 7

From the data presented in Fig. 4 and 5 it is possible to trace the nature of the change in different wave oscillations with an increase in the $R_1 = u_\infty \delta_1/\nu$ Reynolds number. We notice first of all that with an increase in R_1 $= u_\infty \delta/\nu$ the local critical Reynolds number is reduced: When R_1 = 800, 1000, 1200, and 1500, $R^* \cong$ 9,6,4, and 3. Obviously, with a sufficiently high R_1 Reynolds number the local critical $\tilde{R}$ Reynolds number will equal zero. The range of dangerous wave numbers and dangerous frequencies practically does not change with an increase in the R_1 Reynolds number within the limits considered. With a fixed local $\tilde{R}$ Reynolds number, with an increase in the R_1 Reynolds number the range of dangerous wave numbers and frequencies can both increase and be reduced--all depends on the magnitudes of $\tilde{R}$ and R_1. If $\tilde{R}$ is sufficiently low, then obviously

the range of dangerous wave numbers and frequencies will first be expanded with an increase in the R_1 number and then will be narrowed, precisely the same as without roughness. If the magnitude of $\tilde{R}$ is sufficiently great (on the order of 10), then the influence of the unit roughness is manifested as a shift in the direction of very small-scaled pulsations (the range of dangerous frequencies increases and the possible wavelengths for dangerous perturbations are reduced). With an increase in the R_1 Reynolds number a reduction in the range of dangerous wave numbers and frequencies predominates, owing to the suppressing influence of instability in the boundary layer itself.

Comparison between the results obtained and experimental data is satisfactory. Analysis of the experimental data in [4] has demonstrated that an element of roughness becomes the cause of premature turbulence of the boundary layer when the R_2 Reynolds number, plotted for average velocity and average depth of the element, d , is greater than 30 to 40. Here, in our case, under conditions most close to experimental:

$$\left(R_1 \equiv \frac{U_\infty \delta_1}{\nu} = 1500\right), \quad R_2 \cong 40.$$

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